

Parametric Evaluation of Waveforms for 5G Networks

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ABSTRACT

Over the years, OFDM (orthogonal frequency division multiplexing) has been the preferred wireless broadband multi-carrier technology. Although it offers efficient power efficiency, good spectral efficiency and provides multipath propagation, it has several limitations when it comes to machine to machine communications needed in 5G applications. These limitations include cyclic prefix (CP), sideband leakage and unacceptable Peak to Average Power Ratio (PAPR). There is need to distinctively consider other multicarrier modulation techniques which include but not limited to FBMC (filter bank multicarrier), UFMC (universal filtered multicarrier) and GFDM (generalized frequency division multiplex (GFDM) for 5G communications. Various unique parameters were evaluated here which include spectral regrowth, the impact of amplification on signals of the various waveforms, the robustness of the systems against carrier frequency offset (CFO) and noise impact for AWGN (Additive White Gaussian Noise) as a result of robustness against noise.

KEYWORDS: Modulation, Multi-Carrier, Techniques, Waveforms.

I. INTRODUCTION

Multi-carrier technique uses wideband channels that are divided into several sub channels which has narrow bandwidth. This is against transmitting data over whole bandwidth experienced in single carrier systems. It should be noted that the sub channels bearing information transmits with low bit rate along separate carrier signals [1]. There are obviously advantages that the multi-carrier systems have over single carrier systems which include: overlapping of the spectrum of each sub-channel, which leads to higher spectral efficiency, hence higher data rate; since the bandwidth of each sub-channel is small and the CFO (Carrier Frequency Offsets) are assumed as constant, there is immunity to frequency-selective fading which is considered to be flat; power/data modulation of a sub-channel can be anticipated since power allocation and data modulation for these sub-channels are predictable for deep fading [1].

OFDM (orthogonal frequency division multiplexing) originally the dominant multi-carrier technique, was very effective with high resistance against multipath propagation and fading. Incidentally, OFDM requires high linearity to give good power amplification hence it suffers from various limitations such as CP (cyclic prefix), sideband leakage and high PAPR (peak-to-average-power-ratio) which are draw backs for machine to machine communications in 5G applications. This has fueled the need for distinctive strategies to mitigate the adverse effect of OFDM in 5G wireless communication systems [2] [3].

It is expected that 5G systems should have higher information rate, massive device connectivity, latency and high channel capacity. These will work with improvement in composition of various advanced methods, such as millimeter wave technology, massive multiple input multiple output (mMIMO) technology and scalable OFDM methods [4]. Various subcarriers and QAM (quadrature amplitude modulation) evaluation schemes used to evaluate PAPR, spectral regrowth, power amplification among others for various modulation techniques such as OFDM, FBMC (filter bank multicarrier), UFMC (universal filtered multicarrier) and General Filtered Multicarrier Modulation (GFDM), among other novel waveform peculiarities are presented.

II. REVIEW OF RELATED WORKS

Features of OFDM was presented in [5] as a point to point communication technique for wireless and wired multi-carrier modulation scheme with negligible complexity. The scheme has several drawbacks which includes large out-of-band emission and limitations in spectral efficiency. These deficiencies as opined can be eliminated by using a proposed modulation scheme such as FBMC [5]. Bit error rate (BER) and power spectral density (PSD) capabilities were exploited for FBMC in conjunction with conventional cyclic prefix (CoCP) under adaptive white Gaussian noise (AWGN). It was found that with few side lobes for FBMC, there was minimal out of band emission. It was also noted that the omission of CP further improves the bandwidth efficiency of the scheme [5].

In [6] the comparison of the air interface of 5G was presented for three multicarrier waveform candidates. The filtered OFDM, the FBMC technique and the UFMC were considered. Attention here was on time/frequency efficiency. For transmission of very small bursts, with tight response needed, FBMC was found not to be appropriate but good for transmitting long sequences. The CP and wide frequency guard for OFDM made it to be very efficient under the same conditions. For UFMC, its performance was very good over OFDM for short burst frame with over 10%. It also outperformed FBMC in this scenario but not for long sequences. Hence, UFMC was proposed for machine to machine communication in this case [6].

Inter-carrier interference (ICI) in OFDM was the problem [7] wanted to solve using UFMC filtering operation applied to a group of consecutive subcarriers. This was to reduce the side lobes that are out of band to minimize occurrence of ICI in the systems especially between adjacent users for synchronous transmission. In this scenario, the user equipment (UE) receives signals from the base stations. The central reception is a coordinated multipoint where joint detection and processing is performed. The result of the scheme was examined and compared with CP-OFDM (cyclic prefix based orthogonal frequency division multiplexing). The work also looked at the effect of carrier frequency offset and its impact on the performance. The outcome was that the OFDM scheme was out-performed by the UFMC in the perfect and non-perfect frequency synchronization for base stations and user equipment.

The focus of [8] was on designing to resolve the issue of high PAPR and spectral efficiency where it concerns waveforms in 5G communication. OFDM, FBMC and UFMC indices for PAPR techniques were analyzed and compared for the different subcarriers and modulation techniques. It was observed that cyclic prefix affects the performance of OFDM, while there was improvement in the efficiency when UFMC and FBMC are used. When filters are used individually on the subcarriers, the cyclic prefix was eliminated. Also it was observed that the PAPR was invariably reduced with increase in the number of subcarriers and that the PAPR is a function of the modulation scheme which changes as the scheme is changed. However, UFMC was seen to be the best technique of the lot as far as waveforms for 5G communication is concerned.

III. MULTI-CARRIER MODULATION TECHNIQUES

A. Orthogonal Frequency Division Multiplexing (OFDM)

In multicarrier transmission, any scheme that has the channel bandwidth subdivided into several parallel sub-channels is a special form of Frequency Division Multiplexing (FDM) [1]. This is generally referred to OFDM. It must be noted that the multiplexing can be in either time or frequency domain. Long term evolution (LTE) and Wireless Fidelity (WiFi) are the two communications systems that use OFDM as the general standard of modulation. Fast Fourier Transformation (FFT) modulation and Inverse Fast Fourier Transformation (IFFT) makes OFDM less complex and very adaptable. The complexity in analyzing receivers is reduced due to equalization of per subscriber scalar technique/scheme. In addition, overlapping of the subcarrier partial spectra increases the spectral efficiency of OFDM systems. There are problems associated with OFDM systems which originate from the high level of the spectral side-lobes which are also rectangular symbols shaped in time. With these, OFDM is susceptible to misalignment in frequency and time considering that the sub-channels are orthogonal to each other. In using OFDM, it is generally filtered to limit out-of-band radiation [1].

The OFDM system model is shown in Fig. 1 where at the data source, the serial binary data are first divided into several parallel subcarriers. The subcarriers are then modulated using independent orthogonal subcarrier frequencies. It should be noted here that the orthogonality between the subcarriers is essential to enable the signals to be separated on getting to the receiver side [1].

Quadrature amplitude modulation (QAM) is generally used with Grey coding to map the bits into complex symbols. The orthogonality in OFDM system is obtainable using orthogonal carrier frequencies for the various subcarriers [1].

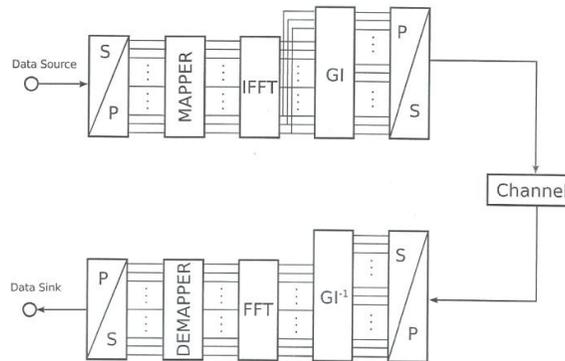


Fig. 1: The Conventional OFDM System.

It should be noted that the time domain signal x_k is achieved by IFFT after mapping by conversion of the frequency domain signal X_k . This is expressed in the following equation [1]:

$$x(k) = \frac{1}{\sqrt{N}} \sum_{l=0}^{N-1} X(l) e^{j2\pi k l / N}, k = 0, 1, \dots, N-1 \quad (1)$$

total number of subcarriers is denoted by N . The cyclic prefix or guard interval is a copy of length L_{CP} of the time domain signal x_k , which due to multi-path propagation is inserted at the beginning of the symbol after IFFT. The length of the transmitted OFDM signal y_o is therefore $N + L_{CP}$. This can be expressed as [1]:

$$y_o(k) = \begin{cases} x(N - L_{CP} + k) & \text{if } k < L_{CP} \\ x(k - L_{CP}) & \text{otherwise} \end{cases} \quad (2)$$

The signal that is transmitted over the channel is initially converted from parallel signal to serial signal and there is reduction of the spectral efficiency due to the insertion of guard interval. The thermal AWGN corrupts the received signal r_o , which can be expressed as [1]:

$$r_o(n) = h(n) * y_o(n) + w(n) \quad (3)$$

$w(n)$ denotes the AWGN with zero mean. In the OFDM system, the receiver will split the received serial signal to parallel in order to remove the inserted guard interval. This guard interval may be overlapped with an existing OFDM symbol. This happens as a result of the linear convolution between the carrier to interference ratio (CIR) and the transmitted signal. The ISI (Inter-Symbol-Interference) can very well be mitigated in as much as the maximum time delay of the channel is smaller than the guard interval duration, hence from Eqn. (4) [1]:

$$L_{ch} - 1 \leq L_{cp} \quad (4)$$

FFT operation is then performed to the frequency domain signal:

$$Y_o(k) = \frac{1}{\sqrt{N}} \sum_{l=L_{cp}}^{N+L_{cp}-1} r_o(l) e^{-j2\pi(L-L_{cp})k/N}, k = 0, 1, \dots, N-1 \quad (5)$$

If Eqn. (4) is satisfied, then Eqn. (5) can be simplified further using Eqn. (1);

$$Y_o(k) = H(k) X(k) + W_o(k) \quad (6)$$

note that $W_o(k)$ is the N-point FFT for $w(n)$ as given by [10, 11]. Furthermore, the statistical properties of $w(n)$ is not affected by the N-point FFT. It therefore follows that with the same variance, $W_o(k)$ is zero mean of the AWGN. From Eqn. (6), the ISI is seen to be well under control as the sub-channels will be flat fading channels. The receiver then

needs an equalizer with one-tap and depending on the knowledge of the CFO at each subcarrier been known by the receiver it is possible to obtain the transmitted symbol given by [1]:

$$\hat{X}(k) = \frac{Y_o(k)}{H(k)} = X(k) + \frac{W_o(k)}{H(k)} \quad (7)$$

It therefore follows that in data communication, there is need to estimate the $H(k)$ as it is very necessary. At the data sink, the estimated symbols are then decoded at the receiver.

B. Filter-Bank Multi-Carrier (FBMC)

The FBMC scheme has a filter per sub carrier which means that each subcarrier is filtered individually. This improves the scheme to withstand Inter Carrier Interference (ICI) effects. The filters employed for FBMC systems have lengths that are many times the number of the total subcarriers. This is however a disadvantage when transmitting uplink short bursts because of the filter length. This hampers applications for 5G communication systems. [9]. Typical FBMC carrier technique is shown in Fig. 2 (a) and (b) for the transmitter and receiver respectively.

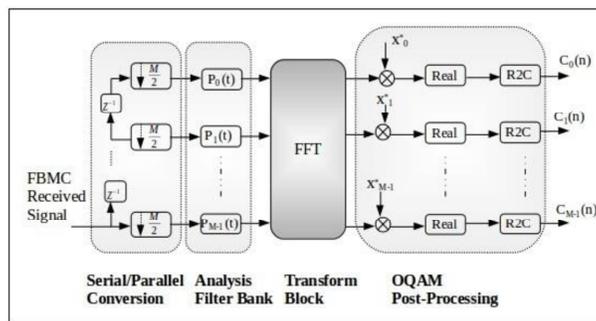


Fig. 2a: FBMC Transmitter Technique

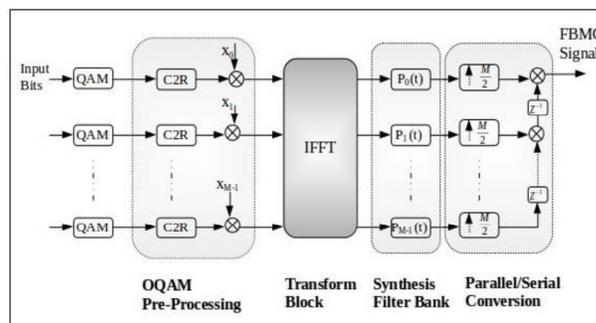


Fig. 2b: FBMC Receiver Technique

Streams of binary data from the transmitter are mapped as Offset QAM (OQAM) symbols and FMBC modulation is employed. The complex data which are imaginary and real are not transmitted directly. They are separated with half symbol duration. The filtered symbols which are in frequency domain are fed to the IFFT. The FBMC coupled Offset QAM preserves the orthogonality, and the real part of the FBMC symbols are depicted in Eqn. (8) [10]:

$$x(t) = \sum_{k=-\infty}^{\infty} \sum_{n=0}^{N-1} j^{n+k} s_{k,n} g\left(t - k\frac{T}{2}\right) e^{j\frac{2\pi}{T}nt} \quad (8)$$

where n is the subcarrier and k is the symbol index,

The total number of the subcarriers is N and the rectangular pulse is $\text{rect}(\cdot)$ which has the symbol period of T and $s_{k,n}$ represents the data symbol of n th subcarrier at k_{th} time interval.

The time and frequency localization is very poor for rectangular pulses, but OFDM systems adapted with rectangular pulse are so sensitive against frequency mismatches and channel noises result in poor time and frequency localization.

However, real parts of the symbols are considered in FBMC system to achieve the good time and frequency localization. FBMC works better in 5G because of its robustness against distortion and high spectral efficiency compared to OFDM

C. Universal Frequency Multi-Carrier (UFMC)

The UFMC system works with division of the bandwidth. This is done in sub bands which have corresponding subcarriers. The system model of the UFMC is shown in Fig. 3. The sub-bands of the subcarriers signals are in frequency domain and have to be converted to the time domain by performing Inverse Discrete Fourier Transformation (IDFT) operation on the sub-bands. After performing the IDFT, the output signal is filtered by the finite impulse response (FIR) filter. This output is given by [1]:

$$y_i(k) = x_i * f_i = \sum_{l=0}^{L-1} f_i(l)x_i(k-l), \quad k=0, \dots, N+L-1 \quad (9)$$

where N is the total number of subcarriers, x_i is the filtered output signal, with length L and f_i is the FIR response.

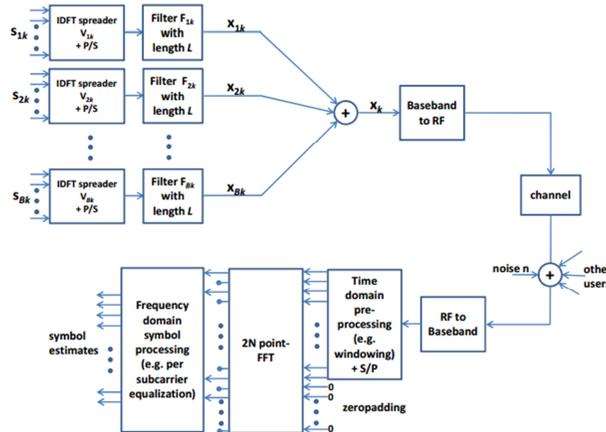


Fig. 3: UFMC System

From Eqn. (9), due to the linear convolution for x_i and f_i the symbol length $N + L - 1$ evolves. To reduce the out of band radiation as found in OFDM, the FIR filter is introduced. In UFMC, the use of properly designed filter in the blocks generally reduces the out of band radiation [1].

D. Generalized Frequency Division Multiplex (GFDM)

The GFDM applies the concept of multicarrier filter bank but in this case, the available spectrum is spread into multiple spectral segments for each user. This concept encourages cognitive radio application for incumbent owners of white spaces that secondary transmitters occupy. The enhanced features GFDM has over FBMC is that the CP can be introduced after multiplexing or before filtering; the subcarriers of GFDM have bandwidths that different for each subcarrier; and circular convolution is used for the filtering for particular number of symbols [9]:

Fig. 4 denotes the GFDM with impulse response of a filter with N samples, while k , m , and n are subcarrier, sub-symbol, and time sample indices respectively. As an additional concept, the data in GFDM is transported in a block wise definition as expressed in Eqn. (10) [9]:

$$g_{k,m}(n) = g[(n - m(K - 1)) \bmod N].e^{-j2\pi \frac{k}{K-1}n} \quad (10)$$

where $g[n]$ denoted the time and frequency shifted version of proto-type filter. $g_{k,m}[n]$ denotes the time and frequency shifted version of proto-type filter $g[n]$. Module N is the circular convolution operation with length N , with M/N as the subcarrier spacing and shifted by K/N in frequency. After filtering, each data block is modulated with exponential sub-carriers [9].

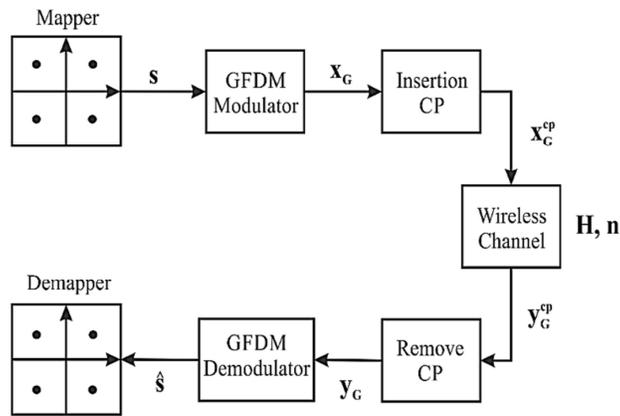


Fig. 4: GFMC System

IV. PARAMETRIC COMPARISON

A. Peak-To-Average Power Ratio (PAPR)

OFDM has high peak-to-average power ratio (PAPR) which is a disadvantage and crest factor reduction (CFR) techniques are typically used to reduce it. Digital Pre-Distortion (DPD) algorithm is then used to correct any distortion implied by the hardware used to amplify the signal. There is need to have efficient power amplifiers to effectively employ these techniques. The resultant effect is reduction in PAPR, spectral efficiency and spectral regrowth [9]. OFDM, FBMC, UFMC and GFDM waveform signals of similar parameters are compared as shown in Table 1 and the plot of the parameters is shown in Fig. 5.

Table 1: Parameters for OFDM, FBMC, UFMC and GFDM Signal Waveform

Waveform Type	OFDM	FBMC	UFMC	GFDM
Number of Subcarriers	2048	2048	2048	2048
Number of Active Subcarriers	1200	1200	1200	1200
Guard subcarrier	424	424	429	424
Subcarrier Spacing	15kHz	15kHz	15kHz	15kHz
Cyclic Prefix Length	144 Samples	144 Samples	144 Sample	144 Samples
Filter	-	RRC, a = 0.1	Dolph-Chebyshev	RRC, a = 0.1
Filter Length	-	-	60dB	-
Number of subbands	-	-	40	-
Payload, Modulation	PN9, QPSK	PN9, QPSK	PN9, QPSK	PN9, QPSK

Source: [9].



Fig. 5: OFDM (yellow), FBMC (blue), UFMC (green) and GFDM (orange).

It was observed from Fig. 5 that FBMC, UFMC, GFDM are more spectrum agile and in particular, FBMC and UFMC offer also significantly lower PAPR and have therefore clear design advantage from RF Frontend perspective. It has to be noted that OFDM is a fully standardized technology and therefore uses channel coding and scrambling to randomize the data that is to be transmitted. Work is still been done on FBMC, UFMC and GFDM which are Physical Layer concepts [9].

B. Spectral Regrowth: OFDM, FBMC, UFMC, GFDM

Comparison of spectral regrowth of FBMC, UFMC and GFDM with OFDM is a key factor for 5G communication. Fig. 6 shows FBMC (blue), UFMC (green) and GFDM (yellow) and OFDM (yellow) waveforms with the parameters chosen accordingly in Table 1.

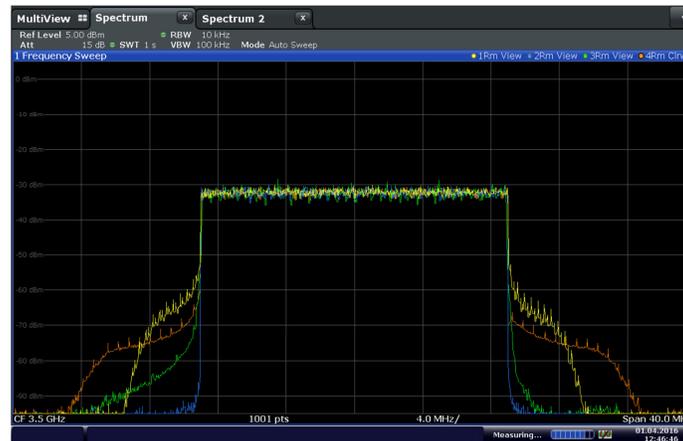


Fig. 6: Comparison of OFDM, FBMC, UFMC and GFDM signals compared for Spectral Growth.

For the demonstration in Fig. 6, the signal generator is connected directly to a spectrum analyzer. The 5G waveforms perform better than OFDM obviously as can be seen [9].

C. Impact of Power Amplification

Fig. 7 compares OFDM, FBMC, UFMC, and GFDM configured as per the parameters of Table 1. This is to observe the impact of power amplification on the various waveforms for frequency range of 50 MHz to 4000 MHz. The gain of the amplifier is 20 dB while the input power is 0 dBm with a maximum of +20 dBm.

It was observed that at the input of 0.00 dBm, the power amplifier starts to go into saturation and is in compression for higher input power [9].

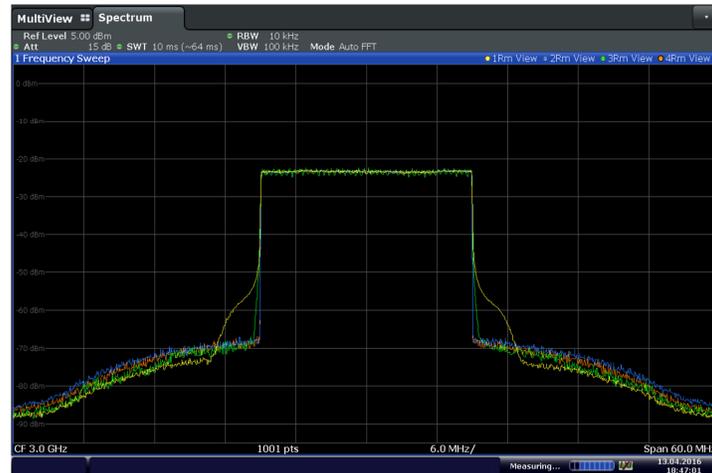


Fig. 7: OFDM, FBMC, UFMC and GFDM signal with amplifier gain of 20 dB.

For -2.00 dBm input power to the amplifier using the same signal parameters and measurements, Fig. 8 spectral advantages of the 5G waveforms is significantly diminished when compared to that of the OFDM and is almost gone when an input power of 0.00dBm is applied [9]. The significance is that the various waveforms will perform much the same under adverse conditions.

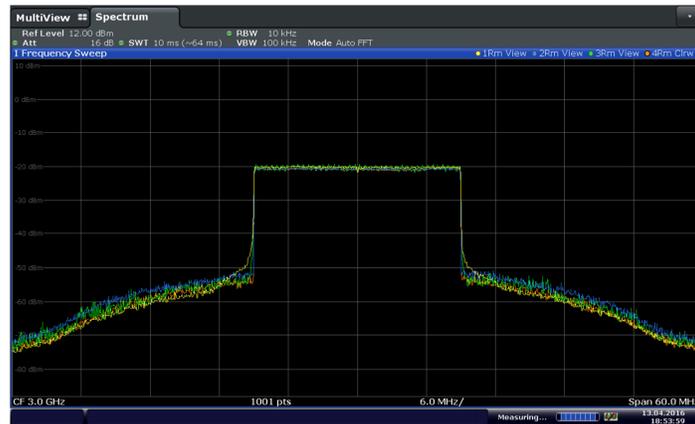


Fig. 8: OFDM, FBMC, UFMC and GFDM signal with amplifier input power of -2.00 dBm.

D. Robustness against Carrier Frequency Offsets (CFO)

Due to transceiver components impairments carrier frequency offsets (CFO) occurs. This results in interferences between the carriers in the demodulation of the signal. The resultant effect is the increase the number of incorrect demodulated symbols. The CFO is related to the subcarrier spacing where a CFO of 0.1 corresponds to $0.1 * 15 \text{ kHz} = 1.5 \text{ kHz}$. The GFDM since it has greater spacing than the other waveforms requires application of CFO for absolute evening of the symbols. It is assumed that the phase rotation is perfectly synchronized. Fig. 9 shows simulation results for normalized CFO against symbol error rate of 12 dB E_s/N_o with QPSK. The simulation is for an applied CFO to the signal against an AWGN channel with constant E_s/N_o (12dB) and applied CFO to the signal. It should be noted that the OFDM curve is the reference as its properties are better understood [9].

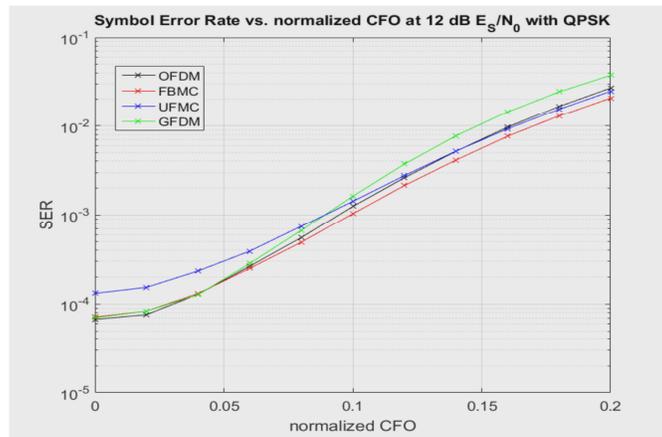


Fig. 9: Symbol Error Rate for increasing values of Carrier Frequency Offset normalized to carrier spacing (15 kHz) at 12 dB E_s/N_0 .

As can be seen from Fig. 9, FBMC when compared to OFDM is more robust mainly due to the fact that shaping the subcarriers the side lobes are reduced in FBMC. In the case of UPMC where simulation is with a rectangular pulse shape, the same behavior as in OFDM was observed. Therefore, a filter length of 146 was chosen. In the case of no carrier offset there is a higher error level, because the bit energy has to be split up to the filter tail. Increasing the CFO gives better frequency performance per sub-bands. The GFDM shows a performance that indicates its sensitivity to CFO thus showing the worst behavior of all the three waveforms when compared to OFDM [9].

E. Impact of Noise

An Additive White Gaussian Noise (AWGN) was simulated for the analysis of the system robustness against noise. Generally, noise power can be defined as the ratio of energy per bit to noise power per Hertz (E_b/N_0). This ratio can be said to be proportional to the signal to noise ratio (SNR). The measurement of the bit error rate (BER) for several SNRs [9] is shown in Fig. 10.

Notably, the various waveforms show good performance that is evenly matched as they reach the theoretical transmission limit in an AWGN. The significance is that they do not introduce self-interference in the symbols or carrier. GFDM and FBMC accomplish this by deploying OQAM (Offset QAM). The CPs for OFDM and GFDM are not considered here for simplicity thereby eliminating energy splitting issues. Various assumptions were made in this comparison to even the odds on OFDM. Over all, with respect to CP filter response, OFDM, GFDM and UPMC were considered the worst performers [9].

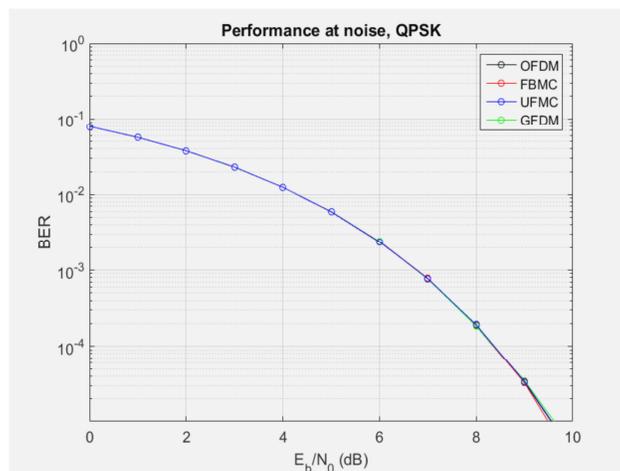


Fig. 10: Bit Error Rate (BER) for increasing values of Energy per Bit by Noise Power per Hz (E_b/N_0).

V. CONCLUSION

5G waveform candidates – FBMC, UFMC and GFDM were analyzed for various parameters and compared with OFDM. The reference points were for peak-to-average power ratio, spectral regrowth, carrier frequency offset and impact of noise. As much as the 5G waveform candidates show improved performance over OFDM, these advantages diminish with amplified signals as the out-of-band emission is concerned. More research, testing of hardware and experiments are needed for further investigation into the various advantages the new waveforms exhibit.

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